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On Several Trends of Crystallization in Intermediate Magmas from Victoria, Australia

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Abstract: The ternary diagram of the system An-Ab-Or is applied to a discussion on the trend of crystallization in four intermediate magmas from Victoria. Variations are shown in the crystallization paths of the four series, depending on the composition of the initial liquids, temperature of crystallization of feldspars and the extent of reaction between the liquids and early feldspars. A correlation is made between optical properties of feldspars and their crystallization history. There is a relationship between the 2V values of the feldspar phenocrysts and the path of crystallization of their corresponding host rocks.

INTRODUCTION

Tuttle & Bowen (1958) constructed a ternary diagram of the system $CaAl_2Si_2O_8$-$NAlSi_3O_8$-$KAlSi_3O_8$, based on data in the literature on the composition of two co-existing feldspars and the host rock or the groundmass of extrusive rocks. With the aid of this diagram they discussed the general trend of crystallization in trachytic, rhyolitic, and phonolitic magmas. Important data on the feldspar ternary diagram was also provided by Carmichael (1960, 1963 and 1965).

Thirty-three intermediate rocks containing alkali feldspars were collected from the Newer Volcanic Series of the Tertiary alkaline province in Victoria. In addition to normal petrological examinations, feldspars were separated and studied by chemical and optical methods.

The rocks and their feldspar phenocrysts (Table 1) were plotted in the ternary An-Ab-Or diagram (Fig. 1). The significance of this in relation to the course of feldspar crystallization is discussed below and correlated to some optical properties of the feldspars.

PETROLOGICAL BACKGROUND

The Victorian intermediate rocks are divided into four series: (a) Sugarloaf trachytes, (b) Macedon trachytes, (c) solvsbergites, (d) Trentham trachytes. The first three series are located around Mt. Macedon. There may have been a petrogenetic relationship between the first two series, but clear evidence to support this possibility is not available. Generally, the Sugarloaf trachytes outcrop a few miles N. of Mt. Macedon, and the Macedon trachytes appear on the mountain itself. There is no intermingling between the two. The Macedon trachytes and the solvsbergites, on the other hand, appear in the same areas. In some cases the trachytes surround solvsbergite outcrops. Hand specimens of the two rocks occasionally appear to be similar. One rock and its feldspar phenocrysts (No. 7, Table 1) were found to have intermediate chemical compositions between the rocks and the feldspar phenocrysts of these two series. It is considered that the Macedon trachytes and the solvsbergites originated from the same magma by differentiation and stratified separation. The Trentham trachytes are a separate unit, geographically remote from the other series.

THE MAGMATIC EVOLUTION OF THE TRACHYTES AND SOLVSBERGITES

(a) *Sugarloaf trachytes*: These are of different generations (Skeats & Summers, 1912). The section S-Si (Fig. 1) represents Sugarloaf trachytes which contain resorbed phenocrysts of alkali feldspars and olivines (samples Nos. b and c, Table 1). They are in association with alkali feldspar bearing basalts, and are believed to be products of a contaminated trachytic magma. They are particularly lime rich. Qualitative microscopic observations indicate that these rocks gave rise to two feldspar assemblages, as might be expected (Carmichael, 1963). Section Si-Sii of the line S-Sii represents Sugarloaf trachytes of a different generation. In this group the rock 23a contains

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plagioclase and alkali feldspars and the rock 23 contains only alkali feldspar. Duc to lack of quantitative data on the feldspars of rocks 23a, b, c, a discussion on the crystallization of these rocks is not attempted and only the possible trend of liquid migration is given.

Detailed information on the feldspar of rock 23 is available. The only feldspar present is a sanidine cryptoperthite ($2V = 39{\cdot}5°$), which has a lower lime content than the rock. This is in opposition to the observation that natural alkali feldspars are usually enriched in lime relative to the liquids from which they crystallize (Carmichael, 1963) and suggests, in contrast to Carmichael's concept, that if the feldspathic components of the initial liquid contain more anorthite than that held in the early crystallizing sanidine, then the plagioclase crystals will not be completely resorbed, or may not, in fact, be resorbed at all.

A possible explanation for this uncommon occurrence of a single alkali feldspar having a lower content of lime than the rock is the following: As was mentioned above, the Sugarloaf trachytes were probably contaminated and erupted in the course of a few generations. Thus, it is possible that feldspar No. 23 was strange to rock No. 23, and had originally crystallized in a magma of a different composition which was altered before the eruption. This feldspar is fresh (resorption is rare, Table 2, Bahat, 1970) and considering the difference in composition between the rock and the mineral, a short contact between the two is assumed.

(b) *Macedon trachytes*: The normative bulk feldspar of these rocks falls below the feldspar solidus towards the Or corner of the diagram (the feldspar solidus is shown by the phenocrysts Nos. 12, 14, 16, and 17). As expected (Carmichael, 1960), these rocks solidified wth a single feldspar. Although the rocks vary in composition (from M to Mi), the composition of the feldspars remains nearly the same except for No. 17. This is lower in lime, because it was crystallized in contact with volatiles (as indicated by the porosity of the rock), and this decreased the crystallization temperature of the feldspars (Tuttle & Bowen, 1958). The similarity in feldspar composition as opposed to gradual change in rock composition indicates that the feldspars had been crystallized prior to the differentiation and stratification of the Macedon trachytes and that the eruption occurred a short time after the stratification and hence impeded a prolonged reaction between the various flows and the feldspar phenocrysts. The feldspars of the Macedon trachytes crystallized essentially under equilibrium conditions: they started as plagioclases which later on reacted with the liquid and

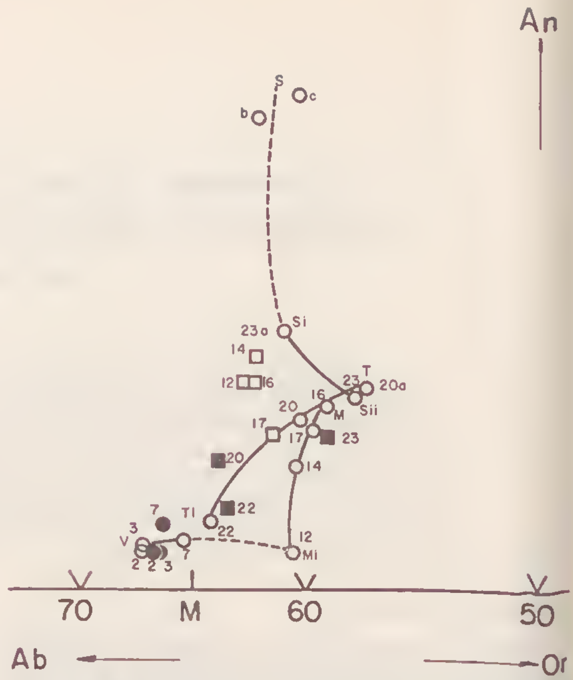

FIG. 1—Diagram of a part of the system An-Ab-Or. The various curves show the trends of liquid migration of several trachyte and solvsbergite series from Victoria.

S-Si-Sii—Sugarloaf trachytes.
M-Mi —Macedon trachytes.
Mi-V —Solvsbergites.
T-Ti —Trentham trachytes.
○ —Trachyte and solvsbergite rocks.
■ —Feldspars from Sugarloaf and Trentham trachytes.
□ —Feldspars from Macedon trachytes.
● —Feldspars from solvsbergites.
M —The minimum on the alkali feldspar join at 500 Kg/cm² water vapor pressure (Tuttle & Bowen, 1958).

gradually gave place to a crystallization of anorthoclases. In these feldspars albite and pericline twins are common, and single Carlsbad twins are absent (Table 2, Bahat, 1970). Zoning that can be observed in the feldspars indicates that the equilibrium crystallization was somewhat disturbed by fractionation.

(c) *Solvsbergites*: The feldspar phenocrysts of the solvsbergites have similar compositions and their solidus is shown by the feldspars Nos. 2 and 3 in Fig. 1. One exception is sample No. 7, which is somewhat richer in lime. The solidus of the solvsbergites is displaced towards the Ab corner in respect to the feldspar phenocrysts of the Macedon trachytes. It is also poorer in lime, and therefore probably indicates a lower temperature of crystallization (Tuttle & Bowen, 1958). On the ternary feldspar diagram the rocks and the feldspar phenocrysts show similar compositions. According to Tuttle & Bowen (1958), crystallization ends when the alkali feldspar crystals react with the liquid and attain the composition of the initial mixture. Zoning is very faint or absent, and idiomorphic forms are common. The compositions of the rocks and the phenocrysts approach the Ab-Or minimum (Tuttle & Bowen, 1958), but do not reach it. The feldspar crystallization in these rocks was not affected by fractionation, and the precipitation of a single alkali feldspar was completed under equilibrium conditions.

Edwards (1938) observed two generations of alkali feldspar phenocrysts in the solvsbergites: Anorthoclases of an early stage grown together in allotriomorphic aggregates, characterized by fresh crystals, showing indistinct tartan twins and faint zoning, and soda sanidines of a later generation, which appeared as individual idiomorphic crystals simply twinned. The present writer also observed these differences with the exception that with the aid of mineral separation techniques it was found that in fact the allotriomorphic aggregates consist of a large number of idiomorphic simply twinned crystals, thus showing that the distinction between the two generations was not clear cut. The close similarity in composition of the rock and the phenocrysts indicates that all the feldspars in the rock have essentially the same composition.

(d) *Trentham trachytes*: The curve T-Ti shows the trend of liquid migration of the Trentham trachytes. Each of the rocks Nos. 20 and 22 contains only a single alkali feldspar. The feldspar No 20 is an anorthoclase cryptoperthite which has a lower content of lime than the rock. The feldspar No. 22 is a sanidine cryptoperthite which has a higher content of lime than the rock. It is considered that in these trachytes stratification and separation of the liquids into the magmas that eventually built the Blue Mountain and Mt. Wilson (Nos. 20 and 22 respectively) had preceded the feldspar crystallization (as opposed to the development of the Macedon trachytes).

Let us consider again the observation made by Carmichael, mentioned above. The acid rocks investigated by Carmichael (1960 and 1963) were generally expected to have a lower liquidus than the trachytes (Carmichael, 1965). It is expected that this would promote a crystallization of two feldspars (Tuttle, 1952). The trachytes investigated by Carmichael (1965, Fig. 2) were generally either close in composition to the two feldspar surfaces or were particularly anorthite rich (10% anorthite or more): again, conditions

TABLE 1. Chemical Analysis of Trachytes and Solvsbergites and Their Feldspar Phenocrysts

	2	3	7	12	14	16	17	20	22	20a	b	c	23	23a
SiO_2	66.84	65.23	64.73	61.40	60.60	60.70	60.64	57.60	58.60	57.63	51.52	54.06	55.95	55.02
Al_2O_3	17.80	17.00	17.50	20.02	18.80	18.53	18.60	18.81	19.20	18.61	16.58	17.13	18.10	19.02
Fe_2O_3	2.38	3.85	4.03	1.39	3.49	4.24	4.32	2.67	3.91	2.36	2.38	6.10	8.28	7.34
FeO	0.82	1.18	0.49	2.56	1.94	1.65	1.40	4.41	2.15	4.08	7.68	3.55	0.50	2.18
MgO	0.04	0.26	0.11	0.44	0.68	0.90	0.65	0.89	0.50	0.69	4.03	3.05	3.05	1.57
CaO	0.35	0.46	0.41	0.76	1.55	1.91	1.77	2.05	1.45	2.33	6.10	4.88	1.77	2.78
Na_2O	6.54	6.63	6.63	5.87	5.72	5.13	5.43	6.02	6.82	5.77	4.11	3.97	4.64	4.11
K_2O	4.70	4.79	5.19	5.85	5.49	5.19	5.37	5.33	5.23	5.38	2.99	3.92	4.96	3.69
TiO_2	0.05	0.15	0.10	0.74	0.72	0.69	0.78	0.62	0.15	0.55	2.15	1.95	2.17	2.64
P_2O_5	n.d.	n.d.	n.d.	0.39	0.35	0.35	0.25	0.37	0.06	0.28	0.82	0.48	0.16	0.74
MnO	0.06	0.09	0.08	0.02	0.16	0.13	0.12	0.21	0.12	0.21	0.13	0.20	0.10	0.14
Total	99.58	99.64	99.27	99.44	99.50	99.42	99.33	98.98	98.19	97.89	98.49	99.29	99.68	99.23

Norms of feldspar components in rocks (recalculated to 100 wt%):

Or	31.67	31.36	33.63	38.95	36.24	36.29	36.18	35.67	34.19	37.54	25.26	26.85	37.26	32.18
Ab	66.43	66.16	64.24	59.39	57.50	54.65	55.53	55.54	62.19	51.94	49.09	46.29	52.85	54.45
An	1.90	2.48	2.13	1.66	6.26	9.06	8.29	8.79	3.62	10.52	26.65	26.86	9.89	13.37

TABLE 1. Chemical Analysis of Trachytes and Solvsbergites and Their Feldspar Phenocrysts (cont'd)

	2	3	7	12	14	16	17	20	22	20a	b	c	23	23a
Feldspar components (recalculated to 100 wt%):														
Or	32.14	32.27	31.58	31.40	31.75	31.95	34.48	33.18	34.39				36.87	
Ab	66.66	66.29	64.93	57.81	56.40	57.11	57.69	60.31	61.71				55.05	
An	1.20	1.44	3.49	10.79	11.85	10.94	7.83	6.51	3.90				8.08	
2V	46(1.5)	45(1.5)	53(1)	52(1)	57(2)	57.5(2)	48.5(2)	58(2)	43(2)				39.5(1)	

that naturally promoted a crystallization of two feldspars. Feldspar No. 20 (present study) crystallized under different conditions, from a sodium rich trachyte magma containing a moderate amount of calcium (5%-10% anorthite). It is possible that under such conditions sanidine did not start to precipitate, and consequently, with a continuous reaction of the early plagioclases with the liquid, a lime-poor anorthoclase was developed and the liquid was enriched with calcium. In this rock apatite is in abundance (Edwards, 1938), and the excess of calcium in the rock was accommodated in apatite and aegerine-augite.

When the liquid of rock No. 20 was changed into the liquid of rock No. 22 by lowering the calcium content (accompanied by an increase of the Na/K ratio), a precipitation of sanidine was promoted and the expected crystallization took place (Carmichael, 1960). Early plagioclases were completely resorbed and a single sanidine (No. 22) was formed.

Thus, one can observe several paths of feldspar crystallization in the Victorian intermediate magmas. Generally, with a continued equilibrium cooling of a trachytic magma the early crystallized plagioclases are resorbed by the liquid, enriching it with sodium and calcium. This is partly balanced by the reaction of the early sanidines which enriches the liquid with potassium and impoverishes it in calcium and sodium. Commonly (Carmichael 1963), the end result tends to be a single feldspar with a liquid impoverished in calcium (No. 22). If the reaction is long enough, the compositions of the rocks and feldspars would approach similarity (solvsbergites). In liquids having a moderate amount of anorthite (5%-10%) which are sodium rich, if there is a low rate of plagioclase resorption in the liquid, the end result would be lime rich anorthoclases (Macedon trachytes). Alternatively, depending on the temperature of crystallization and the composition of the rock and initial plagioclases, with a continuous reaction of the plagioclases with the liquid, lime-poor anorthoclases would be developed (No. 20). Crystallization in the latter two processes can be accomplished without a precipitation of sanidines.

PHASE DIAGRAM CONSIDERATIONS IN RELATION TO OPTICAL PROPERTIES OF FELDSPAR PHENOCRYSTS

Carmichael (1960) examined the optical properties of feldspar phenocrysts of some Tertiary acid glasses and classified them for the purpose of his study according to their twinning. Feldspars twinning only on the Carlsbad, Manebach, and Baveno laws (although very fine, shadowy, but optically indeterminate lamellar twinning was persistent) were called alkali feldspars, and either sanidine or anorthoclase according to their symmetry. Feldspars twinning on the above laws and also on the albite, albite-Ala, and Carlsbad-albite laws, and in which very fine lamellar twinning was rare or absent, were called plagioclases.

A somewhat different classification seems to be more characteristic for the Victorian feldspars. All the feldspars having simple Carlsbad twins have also low 2V values (Tables 1 and 2, Bahat. 1970). They are considered to have been crystallized essentially as sanidines. In some cases faint zoning or shades of tartan twinning indicate that the sanidine developed from a plagioclase or anorthoclase which had been nearly completely resorbed in the liquid. All the feldspars from intermediate rocks investigated by the writer, having prominent tartan twins and no simple Carlsbad twins, also had optic axial angles higher than 2V = 48·0°. These feldspars in most cases were also lime-rich. They are considered to have been crystallized as plagioclases or anorthoclases.

Judging by the chemical and optical properties of samples Nos. 4F and 7F (Carmichael, 1960, Table III), and assuming that they are representative anorthoclase phenocrysts of the Tertiary acid glasses, one observes that they differ from the feldspars of the Victorian intermediate rocks by having the combination of low 2V values and high content of anorthite ($2V = 48°$ and $41°$, and $An = 7{\cdot}8\%$ and $10{\cdot}8\%$ respectively).

A correlation between optical observations made on the feldspars and equilibrium diagram considerations gives a new signficance to the optic axial angle. By studying the evolution of the liquids of the various rock series and their feldspars, one can see a repetition of cycles. The Trentham trachytes are an excellent example of a cycle which produced sample No. 20 with a high 2V value, 58°, in early stages of the evolution, and sample No. 22 with a low 2V value, 43°, in a late stage of the liquid evolution. In the Macedon trachytes one observes that the feldspars Nos. 14 and 16, which were crystallized at relatively high temperatures, have high 2V values, 57° and 57·5° respectively. Feldspar No. 17, which is richer in potash and presumably had its later stage of crystallization at lower temperatures, has the lowest 2V value of the Macedon trachytes, 48·5°. The crystallization of all the solvsbergites was very similar, probably under similar temperature conditions, and can hardly be called a cycle. One exception to this was feldspar sample No. 7 which is a lime rich feldspar with a high 2V value, 53°. It is believed that this feldspar was crystallized in a magma in which a separation between the Macedon trachyte and the solvsbergite liquids was not completed. If so, it would be in harmony with the above correlation.

It can be concluded that the 2V value does not indicate an absolute temperature, but that it does indicate whether the host rock belonged to a high or low temperature stage of a certain cycle (early or late stage respectively). Sample No. 17 belonged to a low temperature stage of the Macedon trachytes, but this can be at a still higher temperature than sample No. 20, which belonged to a high temperature stage of the Trentham trachytes.

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REFERENCES

Bahat, D., 1970. Optical and Infrared Studies on High Temperature Alkali Feldspars. *J. geol. Soc. Aust.* 17: 93-102.

Carmichael, I. S. E., 1960. The Feldspar Phenocrysts of Some Tertiary Acid Glasses. *Min. Mag.* 32: 587-608.

———, 1963. The Crystallization of Feldspar in Volcanic Acid Liquids. *Quart. Journ. geol. Soc., London*, 119: 95-131.

———, 1965, Trachytes and Their Feldspar Phenocrysts. *Min. Mag.*, Tilley Volume: 107-125.

Edwards, A. B., 1938. The Tertiary Volcanic Rocks of Central Victoria. *Quart. Journ. geol. Soc. London*, 116: 243-320.

Skeats, E. W. & Summers, H. S., 1912. The Geology and Petrology of the Macedon District. *Bull. Geol. Surv. Vict.* 24: 1-58.

Tuttle, O. F., 1952. Origin of The Contrasting Mineralogy of Extrusive and Plutonic Salic Rocks. *J. Geol.* 60: 107-124.

——— & Bowen, N. L., 1958. Origin of Granite in The Light of Experimental Studies in The System $NaAlSi_3O_8$-SiO_2-H_2O. *Geol. Soc. Amer. Mem.* 74: 153 p.

Notes to Specimens in Table 1 and in the Text

Numbers of specimens in Table 1 and in the text, as well as the data on composition of feldspars and 2V values, correspond to identical specimens reported by Bahat (1969, Table 1). Analyses for rocks Nos. 20a, b, and c are quoted from Edwards (1938), pages 264 and 274 (omitting values of H_2O^+, H_2O^-, and trace elements). The figures for specimen No. 23a are from a new analysis. The analyses which are not quoted from Edwards were made by the writer.

The types of rocks and locations of all the specimens which appear in the text are as follows: 2 and 3, solvsbergite, Camels Hump, Mt. Macedon; 7, solvsbergite, Fawkners Hill, Macedon district; 14 and 16, trachyte, Turritable Falls, Mt. Macedon; 17, trachyte, a small peak 40 yards SW. of the Camels Hump; 20, trachyte, Blue Mountain near Blackwood; 22, trachyte, Mt. Wilson, Blackwood; 20a, trachyte, Babington Hill, Trentham district; 23, 23a, b, and c, trachyte, vicinity of Sugarloaf Hill, NE. of Woodend.